MASSACHUSETTS INSTITUTE OF TECHNOLOGY
WITH
HONEYBEE ROBOTICS

2023 BIG IDEA CHALLENGE: LUNAR FORGE FINAL REPORT

ARTEMIS
STEELWORKS

Advancing **R**eactor **T**echnologies for **E**lectrolytic **M**anufacturing of **I**n-situ **S**teel

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Student Team: Palak B PATEL[1,d,+], Jose SOTO[3,b,+], Zachary K ADAMS[1,a,+], Derek CHAN[3,b,+], Amber COOPER[3,b,+], Jonatan FONTANEZ[3,c,+], Laman JALIL[1,a,+], Christopher KWON[2,b,+], Kir LATYSHEV[1,b,*], Beverly MA[3,b,+], Lanie MCKINNEY[1,b,+], Cesar MEZA[3,b,+], Kristoff MISQUITTA[3,b,+], Hyein NA[1,a,*], Tom NGUYEN[3,b,+], Hezekiah PENDLEY[3,d,+], Lokesh SANGABATTULA[1,a,*], Helena USEY[3,d,+], Alice ZEHNER[3,a,+]

Faculty Advisors: Advisor: Jeffrey Hoffman[b,+] Co-advisors: Antoine Allanore[a,+], Martin Culpepper[d,+], Olivier de Weck[b,+], George Lordos[1,b,*].

October 23, 2023

*1: PhD Candidate. 2: MS Candidate. 3: Undergraduate. a: Department of Material Science and Engineering. b: Department of Aeronautics and Astronautics. c: Department of Electrical Engineering and Computer Science. d: Department of Mechanical Engineering. +: US Citizen. *: International*

Massachusetts Space Grant Consortium. Director: Dr. Jeffrey Hoffman, 77 Mass Ave. 37-219,
Cambridge, MA 02139. Tel (617) 452.2353, email: jhoffma1@mit.edu

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Report has been reviewed and approved by Dr. Jeffrey Hoffman

Massachusetts Institute of Technology & Honeybee Robotics

ARTEMIS Steelworks

Advancing **R**eactor **Technologies** for the **E**lectrolytic **M**anufacturing of **I**n-situ **S**teel

Concept Synopsis

> <u>Extraction of Steel from Lunar Regolith</u>: Functional molten regolith electrolysis reactor with **automation capabilities** and **improved efficiency** for **lunar conditions** to produce multiple useful **steel alloys** and useful byproducts such as oxygen and ceramics. (TRL 4)

> <u>Lunar Steel Manufacturing, Characterization, and Testing</u>: Melting and casting the extracted steel composition to understand and optimize the metallurgical and mechanical properties. (TRL 4/5)

> <u>Analysis for Production of Pressure Vessels on the Moon</u>: Calculations to show that the quality of the produced lunar steel is usable for pressure vessels designed for the moon. (TRL 2)

Innovations – Technology for Lunar Environment

> Steel Extraction in Vacuum Environment: Demonstrated the capability of rapid prototyping steel extraction in a lunar vacuum environment. (TRL 4/5)

> Steel Extraction from Non-Beneficiated Lunar Regolith: Demonstrated not requiring beneficiation to extract steel from lunar regolith. (TRL 4/5)

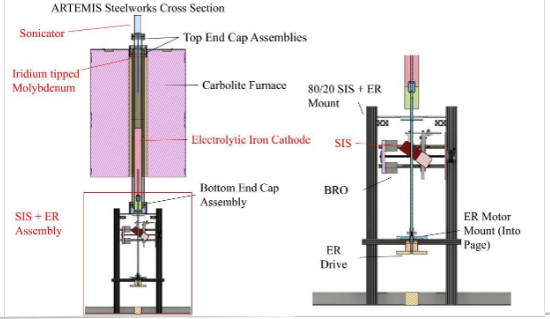
> Automation for Collection of Extracted Steel: Reduce astronauts' labor requirement using a slag and iron slicer for the extraction rod. (TRL 4)

> Improvement of Efficiency of Electrolysis: Using a sonicator to release bubbles that reduce working surface area of the electrolysis electrodes in reduced lunar gravity. (TRL 3)

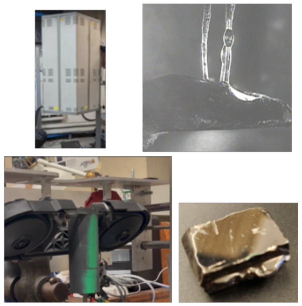
> Steel Manufacturing in Vacuum Environment: Study and optimize the metallurgical and mechanical effect of melting and casting lunar steel in a lunar vacuum environment. (TRL 4/5)

The above innovations further the state-of-the-art by providing contingencies in case beneficiation isn't provided on the moon, demonstrating autonomy where labor is scarce, and studying the different processes in vacuum conditions.

Molten Regolith Electrolysis Reactor Design



Verification Testing Results & Conclusions



MRE Reactor built and tested (Results to be updated)

Steel Extracted in Vacuum Environment successfully, has a composition of ~52% Fe, 46% Ti, 2% Si

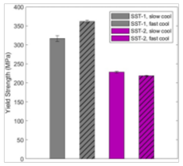
Steel Extracted from Non-Beneficiated Regolith successfully, has a composition of ~70% Fe, 20% Ti, 10% Si

Autonomy of Steel Collection demonstrated successfully by slicing iron rod electrodes as would be collected from the MRE reactor.

Improvement of Electrolysis Efficiency by removal of bubbles using a sonicator.

Steel Manufactured in Vacuum Environment shows smaller grains and higher strength after casting.

Characterization and Testing of Steel for Pressure Vessels shows the quality of lunar steel is usable for building pressure vessel.



Contents

1 Summary Statement

ARTEMIS Steelworks (**A**dvancing **R**eactor **T**echnologies for **E**lectrolytic **M**anufacturing of **I**n-situ **S**teel) demonstrated the production of various alloys of lunar steel, with oxygen as a byproduct, using the Molten Regolith Electrolysis (MRE) process. The metal was extracted from lunar regolith simulant in a vacuum and manufactured in a vacuum. Therefore, the results of our steel characterization and testing are relevant for the prediction of performance of in-situ constructed steel pressure vessels on the moon.

The operational scenario assumes that, by 2028, NASA and its international and commercial partners will be establishing a permanent presence at the lunar South pole. The Artemis Base Camp will be the locus of international and public-private collaboration under the Artemis Accords, helping to bootstrap a lunar economy. As the lunar economy grows, traffic of people and goods will grow with it. Thus, we envision that NASA and its international and commercial partners will have increasing long-term needs for large pressure vessels, both for spacious habitats and industrial-scale storage and operations. However, these may be impractical to transport from Earth due to fairing volume constraints. Accordingly, we selected large steel pressure vessels as the end-use product.

The system of interest is an MRE reactor capable of producing various alloys of steel and other metal products, with oxygen as a useful byproduct. It includes technological innovations to improve its useful life and efficiency, autonomy to save labor time, and demonstrations of subsystems in lunar environment. We built and tested an MRE reactor to produce steel from lunar regolith simulant unenriched and enriched to 40%-grade Fe. The main path-to-flight challenges are the reactors' ability to produce steel in a vacuum environment; reaction inhibition and electrode damage resulting from larger, longer-lived oxygen bubbles in the Moon's weaker gravity; and the need to automate all routine operations. To prepare for a lunar technology demonstration, a prototype electrolysis reaction and steel manufacturing processes were performed under vacuum, a sonicator attached to the anodes to dislodge oxygen bubbles, and an automatic slag and iron slicer were developed for steel collection. The technical objectives are to demonstrate steel-making capability while also quantifying energy efficiency, steel quality, and expected useful life of the electrodes and vessel under different configurations relative to the state of the art.

The comprehensive testing plan presented here includes functional subsystem and integrated testing in Earth and vacuum conditions; validation of the main input, or the enrichment of lunar regolith to 40%-grade Fe by identifying beneficiation technology; and validation of the main output, steel alloys, using tests and calculations to confirm their suitability for the intended primary end-use of large steel pressure vessels. To accomplish these objectives, the reactor is designed to produce sufficient quantities of steel for melting and casting, among other possible manufacturing processes. This enables characterization and testing of the alloys in re-melted and cast form and calculations to assess their applicability to building large pressure vessels. Specifically, testing at MIT included composition analysis using Scanning Electron Microscopy - Energy Dispersive Spectroscopy (SEM-EDS), grain size analysis using etching and imaging, and mechanical testing for hardness and yield strength.

Through the demonstration and characterization of alternative steel alloys, we aim to demonstrate the utility of the proposed technology to the lunar exploration goals of NASA and its international and commercial partners. Further, we quantified targeted improvements in steel quality and reactor longevity and mapped them against alternative designs, operating points, and configurations. Taken together, the proposed design development, testing, demonstration, and experiments aimed to advance the state of the art for producing alloys of lunar steel that shall be well-suited for constructing large pressure vessels at the lunar South pole and other end uses in the lunar metal product pipeline. In addition, the technology concept produces oxygen and ceramic slag, which support additional exploration needs, including transportation, life support, and construction. Finally, as MRE is the only process that can efficiently produce both metals and oxygen using just energy and regolith as inputs, and since MRE outputs can be used to build more MRE reactors, the proposed technology would position the Artemis Base Camp for sustainable long-term growth.

2 Problem Statement and Background

2.1 Metal Production Pipeline Architecture

To envision an entire metal production pipeline architecture for large pressure vessels, we identified 5 driving architectural decisions. Our analysis showed that the most consequential selection for the entire pipeline is the metal extraction process, as it defines possible targeted metals, additional chemical compounds required, extraction environment, operating temperatures, and potential useful byproducts. We analysed the 4 extraction options listed above and selected **molten regolith electrolysis (MRE)** for our architecture. Compared to other processes, MRE does not require any additional inputs beyond an energy source, can process all types of regolith without having to separate fused minerals, has minimal Fe enrichment requirements, and is capable of extracting up to 95% of oxygen contained in the ore as a useful byproduct. MRE also has a current TRL level of 4 and is scalable.[1], [2]. Since iron itself is not a strong material, an additional alloying step with elements like C, Mn or Cr is required. Since these are required in very small amounts, it was assumed that, initially, those elements could be brought from Earth. MRE locked down our choices of **iron** as the targeted metal.

As currently designed, the system assumes the input of lunar soil stock with 40 percent iron content by weight. However, based on Apollo-era lunar soil samples from various sites, regolith can contain anywhere between four to fifteen percent iron by weight, existing in a variety of different minerals [3]. Due to the relative abundance of ilmenite and its energetic favorability for the separation of its constituent iron and oxygen [4] this project aims to use ilmenite-enriched lunar regolith. Although the development of a lunar soil beneficiation system falls beyond the scope of this project, the assumption of a 40-percent (by weight) iron feedstock is more than a reasonable assumption with currently available beneficiation technologies. **Triboelectric charging of lunar regolith particles paired with plate-based electrostatic separation of lunar soil** is currently the most promising technology to achieve such an enrichment of lunar soil – pursued by both researchers at NASA and a series of other agencies. Trials conducted in simulated lunar gravity via a parabolic flight revealed the capacity of achieving between 65 to 106 percent mass beneficiation of ilmenite concentrations in lunar simulant with 15-20 kV of potential difference between the separation plates [5]. Assuming the use of this beneficiation method with a 100 percent mass beneficiation per pass of a given regolith sample and 10-percent ilmenite by weight stock, considering that ilmenite is roughly 30 percent iron by weight [6] one could achieve the desired target of 40-percent iron content with approximately five passes. The only possible challenges to this back-of-the-envelope calculation are that each pass would reduce the mass of a sample by approximately 30 percent (requiring 400 kg of regolith to generate 1 kg of enriched soil) and that there is no literature currently available on the impact of multiple passes on electrostatically beneficiating enriched lunar soil. However, plate-based electrostatic beneficiation of lunar soil still presents itself as the most energetically favorable, well-researched, and robust method of increasing ilmenite concentrations in soil.

The electrical and thermal energy inputs required are assumed to come from fission surface power or solar. The energy source decision will be made during detailed design in Feb 2023 and will be driven by availability of the technology for a CLPS demonstration in a 2028 time frame; Moon to Mars feed-forward potential; uptime and scalability potential (for commercial viability, leading to commercial adoption); which is a key enabling technology for our selected approach.

We chose **casting with subsequent hot and cold rolling** to produce thin metal sheets as our baseline technology for manufacturing metal feedstock for large pressure vessels; our analysis showed that it is a more suitable option for building large structures requiring high strength materials. Casting is a simple process and our testing plan is designed to validate its use on the Moon, where it would also benefit from the absence of an atmosphere, mitigating bubbles in the cast items and corrosion from reaction with atmospheric oxygen. The rolling process is also relatively simple; we have assumed that rolling equipment specialized for the lunar environment would be designed and deployed either by a third party or by the operator of the lunar steel electrolysis facility. We have preliminarily assumed that casting and rolling will allow producing steel feedstock of sufficient strength and quality for manufacturing pressure vessels - this assumption will be validated in this project. Finally, we have assumed that curvature-forming, cutting and welding capabilities will also be available, enabling the in-situ construction of large pressure vessels from lunar sheet steel. As a fallback for the initial stages of lunar metal production, we assumed that pressure vessels can be manufactured from flat parts joined together to approximate curved surfaces, in which case only cutting and welding equipment must be brought to the lunar surface.

2.2 Part of the Architecture Being Addressed by ARTEMIS Steelworks

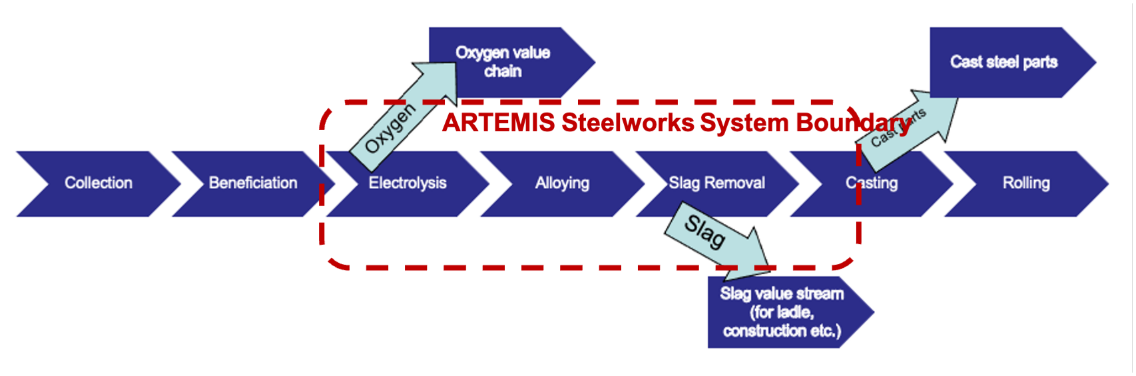


Figure 1: Lunar steel production value chain from regolith to sheet steel, with by-product value chains indicated

As shown above, the choice of the extraction process will significantly impact the entire architecture. This technology is, therefore, on the critical path of developing an ISRU-derived metal production on the Moon. For this reason, our team decided to address this part of the architecture within BIG Idea. Our overall approach is to demonstrate the process of making ‘lunar steel’ by extracting an iron alloy from a lunar regolith simulant via molten regolith electrolysis (MRE), alloying it with different elements, and showing that the resultant material has properties suitable to manufacture steel sheets that then can be used to manufacture pressure vessel shells. For our demonstration, we built and operated a molten regolith electrolysis reactor cell at MIT. Molten steel produced by the cell was collected using a slag and iron slicer to automate the collection process of steel and slag from the MRE reactor. Steel, collected this way, was then melt, cast, and actively cooled in a vacuum environment imitating the conditions on the moon. Multiple samples were collected this way, from regolith simulant representative of the lunar South pole region, under different electrolysis and casting conditions. A battery of tests were performed on each of the samples (those taken after extraction, after melting, and after casting) to measure their metallurgical and mechanical properties and to understand how they change due to the operations performed on them. These lunar steel alloys with their mechanical properties were used to show that the quality of lunar steel that can be made on the moon would be usable for producing pressure vessels. [7]

The proposed technology has five innovations to demonstrate the technology and overcome challenges that be faced in the lunar environment- extraction tests performed in vacuum, extraction tests performed with non-beneficiated regolith to demonstrate the possibility of the production of steel using MRE technology without the need for beneficiation, automation capabilities to collect the iron from the MRE reactor to reduce the need for labor, a sonicator to dislodge oxygen bubbles from the cell anodes to ensure reaction under the reduced lunar gravity and extend the useful life of the electrodes, and steel manufactured in vacuum and fast cooling conditions to understand the metallurgical and mechanical properties of lunar steel manufactured on the moon for pressure vessels.

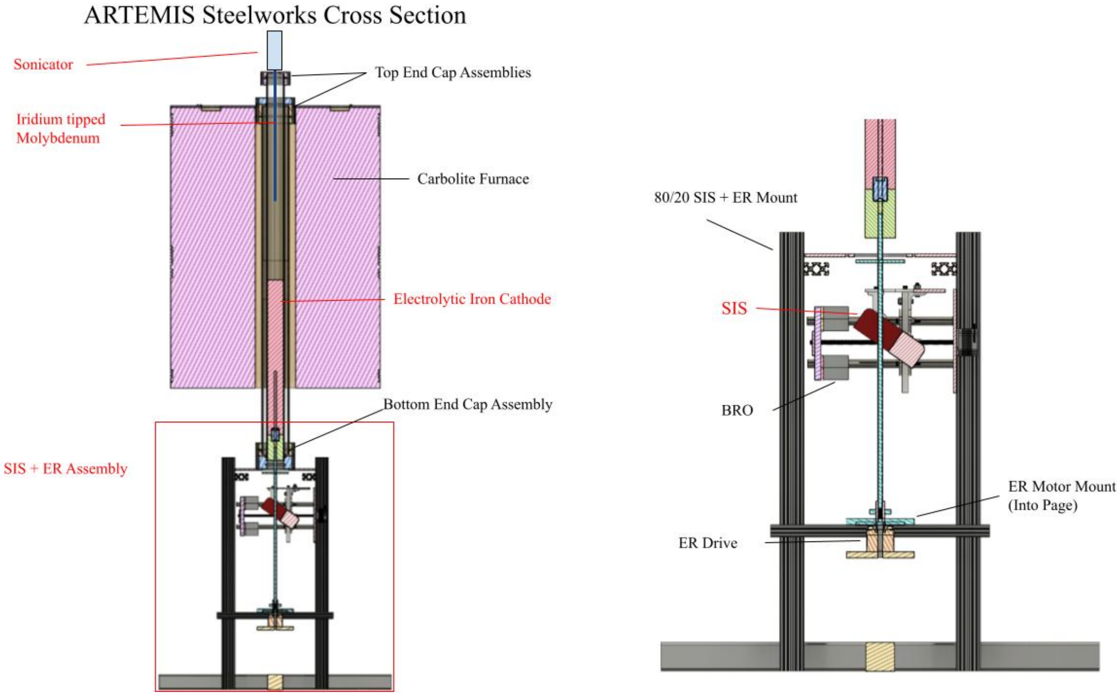


Figure 2: Cross Sectional Render of ARTEMIS Steelworks Prototype

3 Project Description

3.1 Extraction of Steel from Regolith

The goal of the ARTEMIS Steelworks MRE reactor is to enable a larger-scale production of iron metal from a simulant regolith feedstock. To that effort, the reactor consists of two tubes, capped with large aluminum endcaps on each end, inserted into a large Carbolite vertical tube furnace. The tube furnace provides the heating and insulation required to heat and hold materials at temperatures in excess of 1600°C. An image of the tube furnace with tubes inserted is provided in Fig 2. The inner tube of the reactor is responsible for containing both molten regolith and molten iron, while the outer tube acts as secondary containment, in case the inner tube is ruptured. The end caps are flexible components of our design that serve various roles in MRE. Each end cap is fashioned out of solid aluminum, fitted with o-rings to sustain an analog argon atmosphere, a liquid cooling loop, various mounts for system components, like the anode and the gas inlet and outlet. The end cap also provides an interface between the supportive mount and structural stability for the alumina tubes.

The electrolysis experiments run in the MRE reactor consist of three primary stages: loading, heat up/cool down, and operation. In loading, the inner tube is filled with solid, powdered regolith simulant, representing integration into the overall lunar metal pipeline. In these preliminary experiments, the loading is done by hand. In future iterations of the ARTEMIS Steelworks reactor, autonomous deposition of the regolith into the reactor will be done by a hopper or other similar mechanism- this was initially in the scope of the project, but it was deemed secondary to the operation of MRE. The regolith is supported by a large electrolytic iron rod present at the bottom of the reactor, which also serves as the cathode for electrolysis. The rod

Figure 3: MRE Reactor Construction

is inserted from the bottom before loading the regolith. After loading, the furnace caps are replaced and tightened to reseal the reactor. Atmosphere is then purged from the reactor using a pump, followed by an inflow of Argon gas. Once a suitable Argon atmosphere is developed, the furnace is powered on. In heat up/cool down, the furnace is autonomously changing temperature at a rate of 120-180°C per hour. During the operation phase, the furnace is around its set point, 1600°C. The molybdenum rod, serving as the anode, is slowly lowered into the molten regolith, and when electrical contact is established, electrolysis can begin. This will be done at a voltage of approximately 1-3V at a current of 50-70A. Oxygen gas produced during this time will be carried up by the flowing argon and into the [analyzer]. As the iron rod grows during operation, the distance between the cathode and anode ends up not being constant. To solve this, distance will be maintained using the Extraction Rod (ER), resulting in operation requiring little active participation, prioritizing safety and astronaut time. Operation will cease after about an hour, and the furnace will cool down to room temperature, after which the produced metal is extracted using the SIS+ER System. When the MRE reactor is run, we will include information stating the mass of regolith used, its volume in the reactor, as well as the usable iron collected from the reaction. A more in-depth power study will also be recorded and analyzed to be put into the final version of the report. This produced metal will then connect to the rest of the lunar metal pipeline, being remelted, alloyed and processed for consumers. We forsee that the metal produced by ARTEMIS Steelworks will be invaluable to early permanent lunar habitats, being a necessary predecessor to any large-scale lunar base. Because of this, we forsee that ARTEMIS steelworks will have little issues receiving funding from NASA or commericial companies that plan to inhabit the lunar surface long term.

SIS+ER Description This project originally envisioned the use of a circular saw blade to remove any produced iron from the reactor's cathode. After further review and consultation, the team realized that a bandsaw (pictured in Fig. 4) would be most effective in producing a clean cut and most feasible to implement. Any further developments of the SIS required the definition of design constraints based on the project's timeline and available materials. Building a saw from scratch would not only strain the project's budget but also introduce an unnecessary degree of complexity that did not contribute to the technology demonstration of this project's most crucial element: the Molten Regolith Reactor. Therefore, the team selected a portal bandsaw capable of cutting through the diameter of the iron cathode and subsequently performed all designs of the SIS with respect to the bandsaw's dimensions.

The horizontal bandsaw's shape required linear actuation to slice through the iron cathode, introducing the use of stepper motors to drive the chassis forward. Each stepper motor selected had a rated load of 200 pounds to sustain the weight of the bandsaw and the reaction forces experienced by the saw while cutting. To prevent the weight of the motor from shearing the linear actuator rods along which it was driven by the motor, the team incorporated four, load-bearing steel shafts into the design, outfitted with self-lubricating brass bushings to limit friction during motion. Finally, the remaining support structures for the SIS were designed with Aluminum 6061 as a preventative measure for any unexpected loads during the cutting process and to ensure a robust design without creative load-bearing calculations.

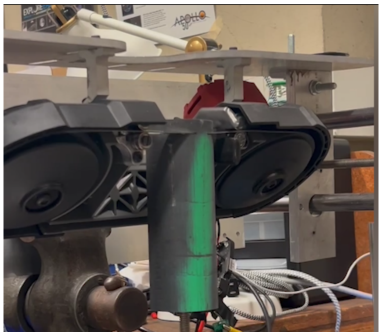


Figure 4: SIS in Action

Currently, the SIS uses 20 volts, operating with a current draw of approximately 4 amperes, drawing a maximum recorded power of 100 W as measured by the team's power supply. The whole SIS measures upwards of 20 kilograms, not including the 80/20 structures used to suspend it in the air for testing. Overall, with the 80/20 structures used during testing, the SIS occupies a space of roughly 1 cubic meter. Approximations are required due to the rather cumbersome subsystem design and the sensitivity of certain elements.

Introducing an automated Back Rod Opposer (BRO) to limit the vibrations of the cathode and secure the iron during

the cutting process proved more time-intensive than expected.
Therefore, although it was conceptualized, designed, and manufactured, the BRO was not integrated into the final prototype of this proposed architecture. However, its integration into a flight-ready system would not prove to be an exigent effort since it operates with the same principles and design considerations as the SIS.

The extraction rod's design and development remained constant throughout the entire design process, from the original proposal even unto the currently prototyped solution. Only two noteworthy design changes occurred during its integration. First, the team introduced a Teflon intermediary between the ER and the iron cathode to insulate the linear actuator's shaft both from the reactor's high temperatures and from the current run through the cathode – otherwise, there was a risk of shorting the motor responsible for extracting the cathode from the reactor. Secondly, because the purchased linear actuator did not drive the lead screw forward unless one end was prevented from rotation, the team incorporated a system of steel shafts paired with an aluminum plate to physically constrain the rod. Either a more refined version of this system would be developed for a flight-ready system, or the actuator selected for a flight-ready system would not require such a constraint to function.

All elements of the slicing subsystem – the SIS, ER, and BRO – were designed to be integrated with the Molten Regolith Reactor via a series of aluminum beams. For the safety of team members and the sensitive elements of the Molten Regolith reactor, the team did not integrate these subsystems, although the infrastructure to do so exists. Currently, for testing, the SIS, ER, and BRO are suspended on a combination of tables and 80/20 aluminum structures.

Operation and Testing Due to supply line setbacks and broken heating elements, operation of the MRE reactor is still in the process of being verified and tested. We will run the MRE reaction several times, focusing on producing a consistent metal character to contextualize our pressure vessel analyses, and to provide a comparison in performance between sonicator and non-sonicator usage. Verification and testing of the SIS system has been performed, and a preliminary test in an external test stand cutting iron proves that our SIS and SIS mount design holds merit. The integration of the ER and BRO were also proven during these tests, verifying that the motor's lead screw combined with the BRO can support the iron during cutting.

3.2 Metal Manufacturing

The manufacturing process seeks to optimize the mechanical and microstructural properties of the metals produced in small scale tests. A simulation of our lunar metal can be melted and casted for characterization and basic manufacturing processes. For each metal produced in small scale testing, the composition was simplified into ratios of the primary metal components - iron, titanium, and silicon. Metal samples of these new compositions were then melted with an arc melter and cooled slowly. A portion of the metal was then recast into a bar and cooled quickly.

The project originally intended to alloy the iron with carbon and to cold-roll the alloy. Alloying with carbon was infeasible due to the constraints set by the arc melter. In the arc melter, the carbon would have vaporized rather than mix with the metal. Attempts to cold roll the cast bars were unsuccessful because the metal was too brittle. Ternary and binary phase diagrams of the relevant iron, titanium, and silicon components showed that materials derived from both the beneficiated and un-beneficiated lunar regolith were primarily composed of intermetallics, yielding a brittle nature.

3.3 Production for Pressure Vessels

The metal produced by the MRE can then be used in the building of lunar infrastructure, especially pressure vessels for habitats or fuel containment. The following models focus on the habitat aspect. Metal validation must be performed to ensure metal produced is safe for habitats in the lunar environment as well as be sufficient to maximize habitat functionality and minimize metal necessary for construction.

The shape of the pressure vessel was decided based on metal efficiency as well as the stress distribution across the surface area. A spherical design was first considered due to its even stress distribution. However, upon consideration of its ability to function as a habitat, a cylindrical design with hemisphere ends oriented vertically was proposed and ultimately decided upon. The dimensions of the cylindrical design would be dictated by necessary living space. The standard ceiling height of 2.75 m for its vertical length will be selected. An internal pressure is set to be 1 atm with the approximation that the external pressure in the lunar environment is 0 atm. Furthermore a safety factor of 4 was assigned to the model. In order to test for this function of the metal, hardness and yield strength tests were conducted. A model was produced in order to determine the volume of steel necessary for the vessel. This model employed a safety factor of 4 and used yield strength and hoop stress to calculate thickness necessary for varying diameters. The diameter will denote the floorspace of these habitats. Further discussion of this model can be found in the Pressure Vessel section of Test Results and Conclusion. This concept assumes that there is limitless supply of lunar steel produced by the MRE reactor in order to provide the necessary stock for any size pressure vessel.

3.4 Summary of Metal Performance Needs

When considering the size of the pressure vessels, inner diameters starting from 7 m to 12 m were considered. They were considered alongside thickness values from 0.0001 to 0.02 m. A factor of safety of 2 was used for the study shown in Figure 5. This number was selected such that there is no abundant excess in order to minimize cost while also considering the safety necessary to use these vessels as habitats. An ambient pressure of 101,325 Pa was selected to mimic the atmospheric pressure on Earth. Given these factors, the largest required yield strength across this range of diameters and thickness is 24,318,000,000 Pa or 24,318 MPa in order to have a diameter of 12 m and thickness of 0.0001 m. The yield strength necessary for a vessel of the same thickness but a diameter of 7 m is 14,185 MPa.

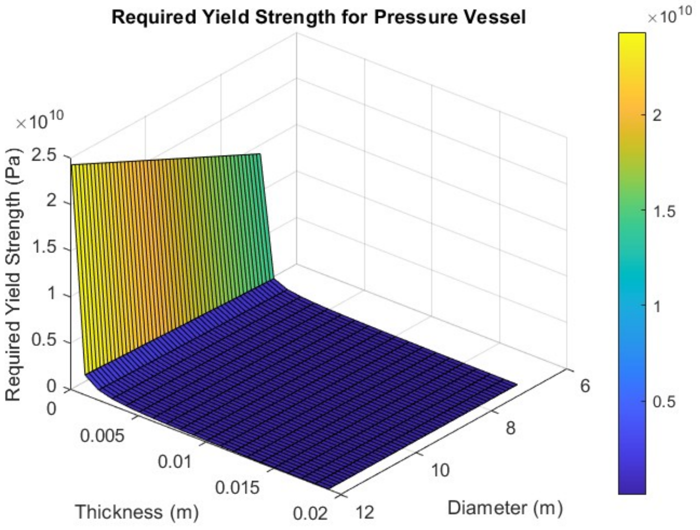


Figure 5: Model showing the yield strengths required for various diameters and thicknesses for the pressure vessel

3.5 Scalability to Operational Concepts

A multi-chamber, multi-SIS+ER reactor assembly can share controls, power and heat sources, regolith hopper and distribution, and metal collection ramps and bins. The scaling provides similar redundancy and fail-gracefully capability. A failed reactor could be taken offline and replaced or repaired while the

Metric	**Unit**	**Metric**	**Notes**
Energy cost of output	kWh/kg	TBD	
System mass	kg	TBD	
Metal per hour	kg	TBD	
Slag per hour	kg	TBD	

Table 1: Estimated Performance Metrics of an Operational-scale ARTEMIS Steelworks System comprising a 20-reactor module.

SST1 (un-beneficiated)				
	Fe	**Si**	**Ti**	**Total**
wt%	0.7310	0.1953	0.0737	1.000
mass (g)	21.931	5.858	2.210	30
volume (cm$\hat{3}$)	2.785	2.515	0.491	5.791
SST2 (beneficiated)				
	Fe	**Si**	**Ti**	**Total**
wt%	0.5180	0.0180	0.4640	1.000
mass (g)	15.540	0.540	13.920	30.000
volume (cm$\hat{3}$)	1.974	0.232	3.089	5.295

Table 2: Table summarizing the weight percent, mass, and volume of Fe, Ti, and Si in each manufactured metal sample.

other reactors in a module continue operating, receiving gravity-fed regolith from the main hopper and delivering metal pucks at the output bin. Operations with these multi-reactor assemblies (say, 20 reactors per assembly) can be scaled up by adding more multi-reactor assemblies. The expected performance of a scaled-up system is shown in Table 1. Please note that this table will be updated before the Forum, once the full-scale prototype experiment is run.

4 Verification Testing on Earth

4.1 Extraction of Metal from Regolith

For the MRE reactor, verification testing was performed on major subassemblies such as the heating subassembly, the argon gas flow subassembly, the tube subassembly, and the power subassembly. The final testing is performed by adding lunar regolith to the MRE reactor and running the reactor for about 24 hours while it performs three functions 1) heating up, 2) electrolysis, and 3) cooling down. The iron electrode would then be removed by SIS+ER and and the slag and steel alloy would be extracted. These final verification testing will be processed soon.

4.2 Metal Manufacturing, Characterization, and Testing

The manufacturing and testing process simplified the EDS results from small scale testing into the three most significant components: iron, titanium, and silicon. High purity materials were mixed in the appropriate compositions to create larger metal samples that could be characterized and manufactured more extensively. The compositions and masses created in the manufacturing process are summarized in table 2.

An Edmund Buehler Arc Melter, an arc melter with suction casting, was used to melt and cast the alloys. The arc melter is similar to a TIG welder, but acts in a vacuum. Like TIG welding, it works by specifying the length of the arc and the current. The melter contains a plasma heating element with argon to arc. The current used was 240A. Two vacuum cycles were performed to achieve the appropriate pressure in the arc melter. By the second vacuum cycle, the pressure was 5.5e-2 mbar. To ensure that the titanium, which had only 99.75% purity, could be melted, a third pump down to a pressure of 5.5e-5 using a diffusion pump was prepared, but was ultimately unneeded. During melting, all samples were remelted once to ensure that they were homogeneously mixed.

Two 30g pucks of equal composition (specified in table 2) were melted for each SST. The pucks were cooled slowly. One of the pucks from each SST trial was then remelted and suction cast in a vacuum environment into a bar which was cooled quickly with water cooled casting molds.

Manufacturing was limited by the composition of the resultant metal - intermetallics are prominent which yields a brittle material. The materials produced in small scale testing contained consequential fractions of titanium and silicon. In SST-1, the Fe-Ti-Si ternary phase diagram predicts $TiFe_2$ and $TiFe_4Si_3$ intermetallics. The Ti-Fe binary phase diagram representative of the metal produced in SST-2 predicts a TiFe intermetallic phase. The brittle behavior of these intermetallic phases made cold rolling and manufacturing beyond casting infeasible.

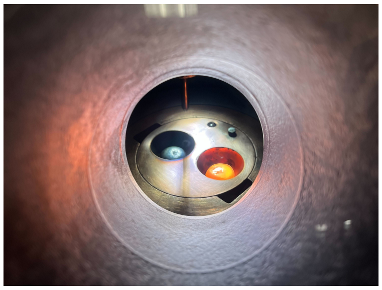


Figure 6: Metal Product

The pucks and bars of each composition were then ground and polished for Vickers hardness testing. Samples were polished to a standard grit of 1 um. For hardness testing, 5 indentations were performed on each sample with a standard load of 9.8N.

4.3 Lunar Environment Technology Demonstration

While MRE reactors have been demonstrated for metal extraction on Earth, the importance of our project is to demonstrate its capabilities on the moon. The following subsections describe the innovation in the process, design, and testing that prepare the technology for the lunar environment.

4.3.1 Metal Extraction in Vacuum Environment

Due to the limitations of the alumina tubes for the MRE reactor, the larger scale process cannot be run under vacuum. The pressure differential at operating temperature could cause the tubes to rupture, which is a major safety issue. As such, the reactor does not support vacuum at all. To bridge the gap between the results from the MRE reactor and metal that could be produced on the lunar surface, small scale electrolysis experiments were conducted under vacuum instead. This small-scale testing was done using facilities provided by Dr. Allanore, which consisted of an optical furnace powered by 4 xenon lamps. Material can be either suspended from above or held from below, and using a fused quartz furnace tube, an inert atmosphere or an evacuated atmosphere can be used. Fig. 7 shows this furnace set up for an experiment. Combined with a Gamry Reference 3000 potentiostat/galvanostat, the setup is able to make electrochemical measurements on material within the furnace tube.

A total of four of these tests were run in the course of this project. In the very first test, a sample of regolith simulant, unenriched in iron was used. Beneficiation on the lunar surface may prove to be an incredibly difficult challenge to overcome, and as such, it is important to understand what metal such a regolith composition would produce. The setup for this sample was to suspend it vertically from the top of the furnace. The composition for this regolith is listed in Table 3. This simulant was made from a mixture of oxides at this composition. This setup allowed for electrochemical tests to be run on the liquid material without any contamination from a container or crucible, as the liquid itself is supported by the solid material above it. Fig. 8 shows this setup in further detail.

Figure 7: An image of the floating zone furnace set up for the un-beneficiated small-scale experiment

LHS - 1							
	SiO2	**TiO2**	**Al2O3**	**FeO**	**MgO**	**CaO**	**Voltatile Oxides**
wt%	49.12	0.63	26.29	3.20	2.86	13.52	3.53

Table 3: Table showing the composition of the regolith simulant used in the small-scale experiments

However, due to the unstable nature and constant bubbling of the molten regolith, this droplet was not very stable. The one succesfull experiment with this setup was one of many failed attempts. To resolve this issue, later experiments instead supported the molten regolith from the bottom, using a container. Initially alumina was used, as it is the container material in the MRE reactor. However, due to the heating rate of the optical furnace, the alumina containers used in these experiments broke due to thermal shock. Finally, this issue was solved by using boron nitride to contain the molten regolith. The boron nitride is reasonably stable when subjected to molten regolith [8] and does not experience thermal shock. With this setup, three more small scale tests were run under a vacuum.

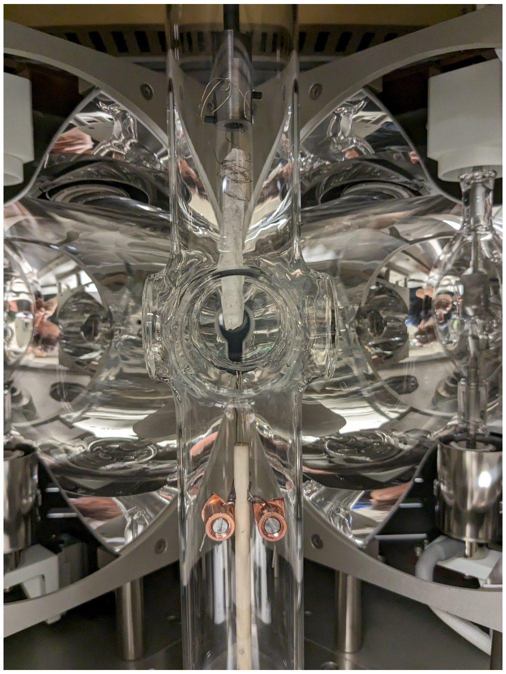


Figure 8: An image of the floating zone furnace set up for the unbeneficiated small-scale experiment

These three tests represented different levels of beneficiation of ilmenite from the lunar regolith. The three samples had ratios of ilmenite to regolith simulant, by weight, of 2-1, 1-2, and 1-4. The regolith simulant used in this case was LHS-1, the composition of which is listed in Table 3 The were melted at approximately 20-30% power of the furnace, which corresponds to a temperature in the range of 1200-1500°C. The wide range is due to the poor thermal control in the furnace, as due to differences in absorption and positioning, temperatures can fluctuate. Using a roughing vacuum pump, a pressure of about 10^{-3} was achieved. While this is many orders of magnitudes less than atmospheric pressure on the moon, this is still much less pressure than on Earth. Additionally, due to gas evolution during electrolysis, it would not have been possible to reach a higher vacuum.

During testing, three different types of tests were run: open circuit potential, cyclic voltammetry, and chronoamperometry. Open circuit potential was done to assess the stability of the molten regolith. Cyclic voltamemtry changes the voltage at a set rate and measures the current. It is useful for determining where the material starts to breakdown. Chronoamperometry is a potentiometric test, which applies a set voltage for a certain amount of time and measures the current. This test was run for 1800s in all small-scale experiments, which gave plenty of time to produce a usable amount of metal. After running chronoamperometry, the samples were removed from the heat and the furnace was powered down. With the experiment finished, the samples were removed from the furnace and cast in epoxy. After grinding and polishing, they were imaged in SEM and analyzed for composition with EDS.

4.3.2 Automation of Collection of Metal

Due to the long lead time of the reactor's alumina tubing, the team could not integrate both the SIS+ER and the MRE. As a result, to showcase the architecture's ability to create iron and extract it without astronaut intervention, the team decided to test both the MRE and SIS+ER independently. Proving the ability to automate the iron process only required a single demonstration of cutting through iron with the proposed design. Therefore, testing the SIS consisted of running the sequence of autonomously raising the extraction rod (simulating the removal of the iron rod from the reactor), proceeding to slice it with the linearly-actuated SIS, and resetting the position of both the SIS and ER. Even if testing required the intervention of a team member to reset a test or repair an unexpected hiccup with the testing setup, a one-time demonstration of the slicing ability would effectively prove the capacity to do so while providing insight into design considerations to be considered during a future iteration of the design.

All testing of the SIS+ER took place in the Space Resources Workshop at MIT. The facility supplied a power supply and emergency stop that interfaced directly with the SIS as well as a vice upon which to secure the device. All other structural elements were secured around the vice, SIS, and equipment employed during testing. For safety during the SIS testing, there was a requirement for a minimum of two people to be present while the saw was operating, as well as two independent emergency stops that would be manually triggered in any unexpected events (e.g., the saw stopping, a motor straining, violent vibrations).

The primary challenge encountered during the SIS+ER verification testing dealt with issues in manufacturing and design. Because of the timeline, the team could not validate the accuracy of the design when it was implemented in real life, leading to a setup that required the removal of a support plate during the final phase of cutting to allow the saw to move forward. Moreover, because of the unexpected constriction of the diameter of a bushing during the press-fitting process, the initial SIS design had limited mobility along its weight-bearing rails, requiring last-minute disassembly before testing. Furthermore, the bandsaw's blade broke in the middle of a test, requiring teammates to swap blades (discussion on addressing this possibility in the infrastructure will be discussed in the path-to-flight segment of this paper). Finally, issues with the wiring in the purchased saw after it was disassembled greatly hampered the ability to perform testing since it would constantly break the circuit, stop the saw, and hence lead to the halting of testing. Due to the timeline, the only viable solution to address these struggles was to repair and address the setbacks as they arose.

4.3.3 Improvement of Efficiency of Electrolysis for Low Gravity

During electrolysis, gaseous oxygen bubbles form on the anodes. However, due to the lunar environment's lower gravity, the buoyancy force is reduced to 1/6$^{\text{th}}$. Consequently, the bubbles could expand and take longer to detach from the anodes, inhibiting the electrolysis reaction and shortening the lifespan of the electrodes due to corrosion. To mitigate this problem, we designed a sonicator attachment in an insulated junction between the anode and the top cap of the furnace to induce vibrations that detach the bubbles while they are still small. This process is low TRL because it is not generally used on Earth; typically, flux is used to change the viscosity of the electrolyte. However, the flux process would be unsustainable for the Moon because it requires a consumable, complicates the operation, and introduces contamination which would then further increase overall complexity.

The sonicator was built from a handheld homogenizer which consists of an ultrasonic transducer powered by a 12-24V/DC adjustable power supply. The sonicator attaches to the furnace inner top cap such that the electronics are outside the alumina tube and protected from the intense heat. The probe passes through the top cap and is sealed with an O-ring. The probe consists of a MACOR® ceramic rod, a molybdenum rod, and the iridium wire. The ceramic rod acts as an electrical insulator between the aluminum caps and the molybdenum rod that passes the current to the iridium anode.

In order to maximize the efficiency of the sonicator, it is necessary that the probe vibrates at its resonant frequency. This resonant frequency depends on both the length of the material and the material itself, so the length should be adjusted to approach the resonant frequency of the bare sonicator. The following formula was used:

$$\text{Half wavelength of standing wave} = \frac{\text{speed of sound in material}}{\text{resonant frequency} \times 2} \tag{1}$$

Based on the tensile modulus, 67 GPa, and density of the ceramic, 2.520 g/cm^3, the speed of sound was calculated to be 5156 m/s. Since this value was close to the speed of sound in molybdenum, 5400 m/s, the two materials were treated as one continuous rod in the calculations. Finally, the resonant frequency of the bare transducer was found to be 53335 Hz using an oscilloscope and sine wave generator.

$$\text{Half wavelength of standing wave} = \frac{5400}{53335 \times 2} = 0.0506\text{m} \tag{2}$$

In order for the probe to be long enough to reach the cathode in the center of the furnace, this value was multiplied by 17, an integer multiple of the calculated half wavelength of standing wave:

$$0.0506\text{m} \times 17 = 0.8602\text{m} = \text{Length of probe} \tag{3}$$

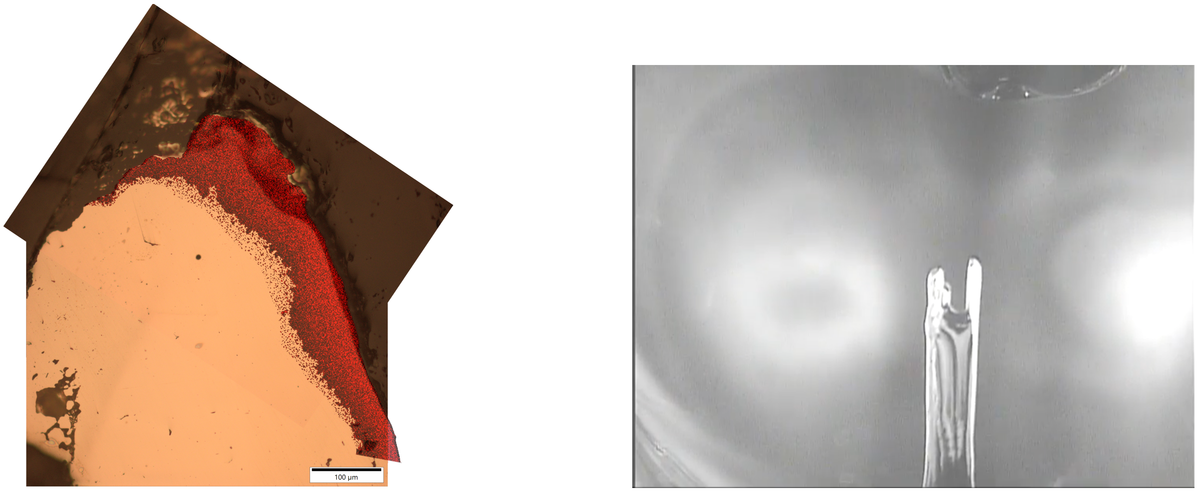
The next step in the sonicator's development would be to record data on the efficiency of the electrolysis reaction with and without the sonicator. Although it is difficult to emulate the effects that lunar gravity has on bubble formation at the anodes, the oxygen bubbles will still inhibit the electrolysis reaction to some degree on Earth. As such, an improvement in electrolysis efficiency under Earth's gravity lends proof that the sonicator will also be effective in the lunar environment. There was also difficulty in simulating molten regolith to test the sonicator prior to integration with the furnace. Since regolith is only molten at very high temperatures, it would be unsafe for initial sonicator testing. To mitigate the safety risk, testing will be performed using carbonated water to mimic the bubbles formed in the regolith.

4.3.4 Steel Manufacturing in Vacuum Environment

The lunar environment was simulated in the manufacturing process through the vacuum of the arc melter. The inert environment of both the arc melter and lunar environment is beneficial to the melting and casting process because it prevents the easily oxidized titanium from reoxidizing. Furthermore, the microgravity of the lunar environment can be simulated by suction casting. Given that melting and casting were successful in the environment of the arc melter and its suction casting, the manufacturing process should also be successful in the vacuum and microgravity of a lunar environment.

Testing facilities were used from across the MIT campus in various laboratories and workshops. The machines used were an Edmund Buehler Arc Melter (an arc melter with suction casting), SEM, EDS, Instron 5969 with 50 kN load cell, and a Micro Vickers Hardness Tester Model No.900-390.

In the melting and casting process it was found that the small scale tests produced very brittle material. Due to budget and schedule constraints, tensile tests of samples at every step of manufacturing was unable to be performed as well as various heat treatments. Furthermore carbon alloying could not occur.



(a) A stitched optical image with EDS overlayed data showing the concentration of iron in the sample

(b) An image taken during the small scale testing showing the very small amount of regolith between the electrodes

Figure 9: Composition of unbeneficiation small scale test and small scale test image

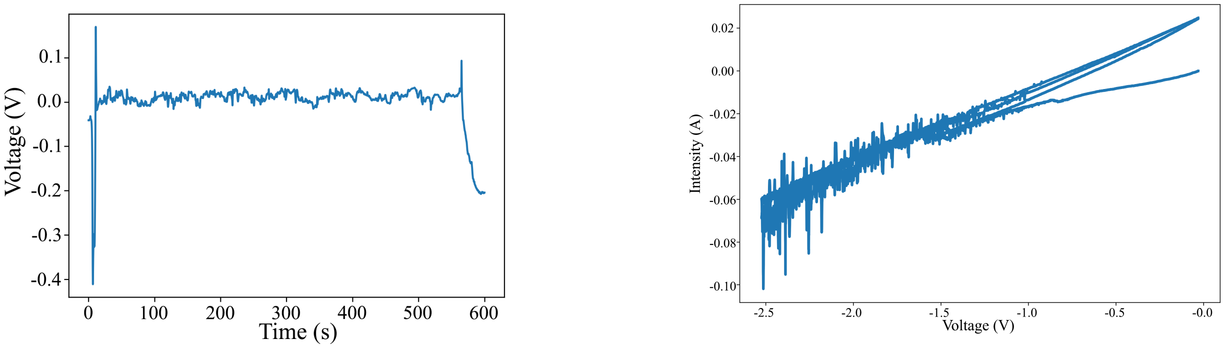
5 Test Results and Conclusion

5.1 Metal Extraction

5.1.1 Steel Extraction in a Vacuum Environment Results

A stitched optical image, with an EDS map of iron overlayed on top is shown in Fig. 9aa. This is from the unbeneficiated regolith sample. This sample is 20-40 wt% iron. It is, unfortunately, quite high in silicon. This is likely a result of the low iron content in the regolith and excessive voltage during electrolysis. The amount of material that was actually involved in this experiment was rather small, as can be seen in Fig **??**b, during the cyclic voltammetry experiments, excessive reducing voltages were reached, which could have deposited more reactive metals than intended. Additionally, silicon and iron strongly alloy together, despite their oxides breaking down at different voltages. Due to silicon having a very low activity within iron at concentration less than 20 wt% [9], it is hard to prevent co-deposition. This testing shows that electrolysis of unbeneficiated lunar highland regolith is certainly possible, and can even make some steel. However, a very small amount of metal was made compared to a very large amount of slag, showing that unbeneficiated electrolysis would be inefficient.

The results of the three beneficiated experiments can be seen in Table 4. Due to the use of ilmenite alone to represent beneficiation, the metals produced have considerable amounts of titanium, while their silicon content is relatively low. Of note is that EDS testing indicated very high oxygen content in these metals. This is not shown in the table, as oxygen is too light of an element to reliably return a signal in EDS. However, this high oxygen content is probably accurate, even if the exact numbers are not. This high content is likely due to the high titanium content and would be deleterious for a metal in use. With better controls during electrolysis, and with lower amounts of titanium, this could be avoided. A select amount of the electrochemical signals from the small-scale tests are shown in Fig. 10a and Fig. 10b. The first figure shows the open circuit potential recorded from testing on the 1-4 ilmenite to regolith sample. The oscillations show that regolith itself is bubbling without any applied current. This nature of the slag can present a challenge in large-scale production, and is likely to be much worse on the lunar surface due to the lower gravity and lower pressure. Bubbles will be able to build up much larger, which can decrease efficiency severely. The second figure shows both cyclic voltammetry performed on the 1-2 ilmenite to regolith sample. From this, it can be seen that the material starts to break down at approximately -0.8V, as evidenced by the increased noise in the signal. This breakdown voltage was similar across all of the beneficiated samples.



(a) 1-4 Ilm-Reg open circuit potential

(b) 1-2 Ilm-Reg cyclic voltammetry

Figure 10: A selection of electrochemical signals from the small-scale testing

	Fe	**Ti**	**Si**	**Al**
1-2	37.2	47.0	7.8	8.0
1-4	46.0	41.4	7.0	6.6

Table 4: Table showing the composition of the metal produced in two of the small-scale beneficiated tests.

In regards to efficiency, the masses of the last two experiments were measured such that the current efficiency could be estimated. Any mass loss during the experiment could be assumed to be entirely due to oxygen evolution. According to Farraday's Law of Electrolysis, this mass loss is directly related to charge transferred via:

$$m = \frac{QM}{F\nu} \tag{4}$$

Where Q is the total charge transferred, M is the molar mass, F is Farraday's constant - 96485 C/mol and ν is the valency of the atom being deposited. Therefore, a mass loss of oxygen can be converted to charge transferred. In the electrochemical tests, the amount of charge transferred is also measured. By comparing these two numbers, the current efficiency of the process can be estimated. This method is very susceptible to mass loss via other methods, and in these tests, unexpected mass losses returned efficiencies well over 100%. Components of the regolith, such as sodium oxide, potassium oxide, and phosphorus pentoxide are voltatile species, and easily boil off of the regolith under vacuum. The recorded mass losses were likely due mostly to this vaporization, as they, combined, make up to 3% of the regolith. The small-scale tests were successful, as evidenced by their production of metal. However, some improvements would be necessary to improve the relevance of these results. For one, a higher vacuum could be implemented and tested, to bring the total pressure closer to what is present on the moon. Secondly, beneficiation would have to be implemented better in choosing sample compositions. As demonstrated by the regolith simulant compositions, not all iron oxide content is due to the presence of ilmenite, meaning iron oxide can enriched without directly increasing titanium content. While these results are promising, the floating zone furnace itself and the setup are not scalable. The maximum system size for this furnace is in the range of 10g. The metal composition results may be scalable, as they well represent lunar conditions.

5.1.2 Molten Regolith Electrolysis Reactor

In the course of constructing the MRE reactor, several factors completely outside of the team's control resulted in large delays. Unfortunately, as a result, the MRE reactor has not been run to demonstrate its performance. Construction, however is underway, and the team is expecting to complete verification of the scaled-up MRE process by the end of October. These results will be updated then.

5.1.3 Electrolysis Efficiency Improvement

Due to schedule constraints, the tests using a liquid with properties more similar to molten regolith have yet to be performed. However, there have been initial visual tests with carbonated water. The sonicator was very effective at eradicating all the bubbles in this liquid. After the final sonicator horn is constructed, more tests with carbonated water will be done. The initial and final pH will be tested, along with the previously done visual test. If the sonicator works as expected, the pH should increase over time as the carbonation is reduced.

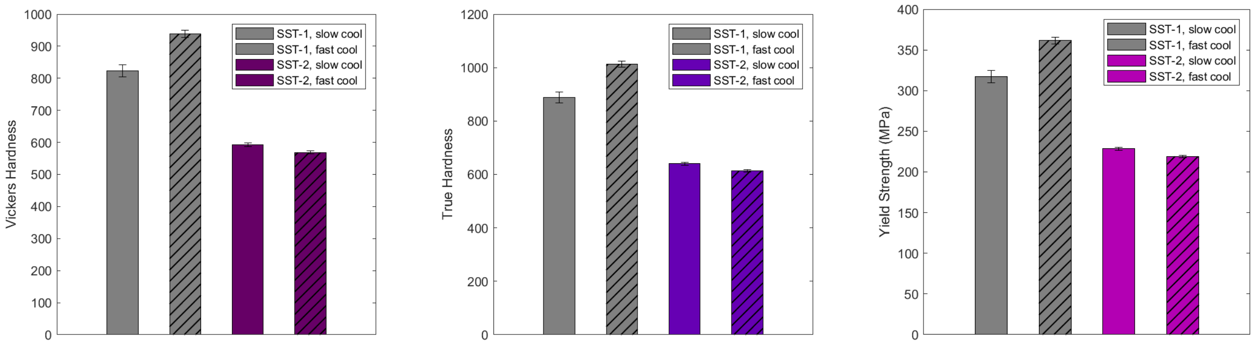
5.1.4 Automation *via* SIS+ER

The team successfully demonstrated the SIS design's ability to slice through cast iron and do so in sequence after the "extraction" of the iron cathode with programming, showcasing the possibility of automating the process. The final cutting sequence through a 2.5"-diameter iron rod took a total of three hours, most of which was performed with limited human intervention. Design changes and mistakes in rapid prototyping that occurred near the end of the system's development required the team to reset and interact with the system during testing (e.g., a new structure that was too small to allow the saw to pass through and a short in the hijacked saw's circuit), but none of these interactions fundamentally disprove the architecture's capacity for automation. In conclusion, the verification test demonstrated the potential to conduct a cutting process with computer commands, meeting the subsystem's proposed objective. However, it is critical to note that there are several key design changes and updates required to fully scale and refine the cutting process – all of which will be discussed in the path-to-flight section of the paper.

5.2 Metal Manufacturing, Characterization, And Testing

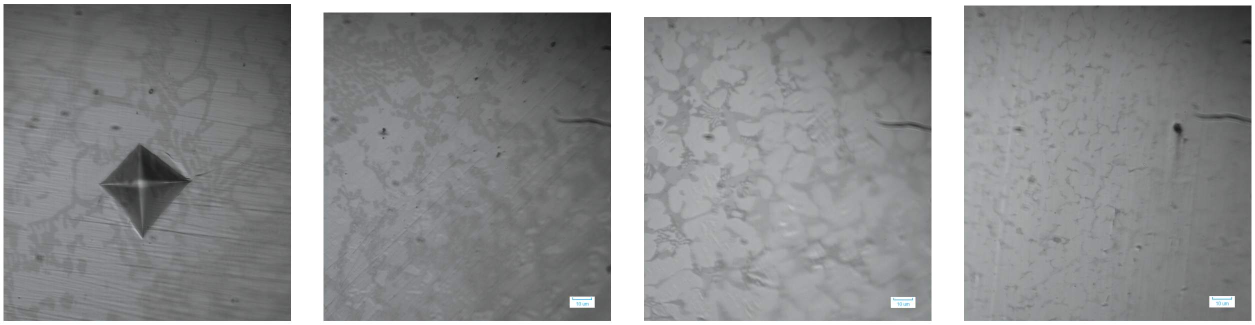
Results indicate that additional research and testing is required for the beneficiation of the lunar regolith. The metals produced in small scale testing. The electrolysis mechanism employed by the reactor successfully extracts iron from lunar regolith, however the initial metal was very brittle due to the intermetallic phases such as $TiFe_2$ and $TiFe_4Si_3$. For characterization, we prepared two different compositions of metal simulants and for each composition, we prepared two samples which have different cooling rates. Micro hardness test was done to evaluate mechanical property and optical microscopy was used to observe microstructure of each metal simulant. Each specimen was indented at five randomized locations for an averaged hardness and yield strength. The Vickers hardness values for the SST-1 and SST-2 metal simulants, slow cooled and fast cooled, are: 823.7±18.9, 938.3±10.9, 593.1±5.6, 568.3±4.5, respectively. The associated yield strengths were calculated by deriving the True Hardness from the Vickers Hardness and using the 3:1 yield strength to hardness relation. The yield strength values are: 317.3±7.3, 361.5±4.2, 228.5±2.1, 219±1.7, respectively.

The Vickers hardness test results show that SST-1 metal simulant has a higher hardness(observed) and yield strength(predicted) than SST-2 (Figure 8). The difference of these two comes from different compositon of metal elements that SST-1 is composed of 73Fe-20Si-7Ti while SST-2 is composed of 52Fe-2Si-46Ti. Also it was shown that the fast cooled sample has a higher hardness than the slow cooled sample. This can be explained by optical microscopy images of SST-1 (Figure 9). There can be several factors that contribute to hardness increment of fast cooled simulant that the fast cooled sample has a smaller grain-like region which will be the primary phase that appeared during cooling step and thus has a larger secondary phase area which are brittle and hard. In addition to that, there will be not enough time for metal elements to diffuse out from the primary phase in the fast cooled simulant which can make the primary phase stronger by solid solution strengthening. This two will be the major factors that can affect and compete to increase hardness of the fast cooled SST-1 metal simulant. Further verification through strength calculation will be necessary to conclude the effect of cooling rate on hardness. On the other hand, the difference between slow cooling and rapid cooling is not significant in SST-2 simulant. As discussed in SST-1, further microscopic and quantitative analysis such as EBSD or EPMA will be needed to compare the effect of grain size, distribution and composition on hardness.



(a) Vickers Hardness (b) True Hardness (c) Yield Strength

Figure 11: The hardness was evaluated for metal simulants of two compositions based on EDS results from small scale testing. For each composition, the metal simulant was subjected to both slow cooling and air quenching as a preliminary evaluation of time-temperature transformation behavior. The hardness was quantified using Vickers hardness tester (a) from which the True Hardness (b) and Yield Strengths (c) were calculated.



(a) SST-1, slow cooled (b) SST-1, fast cooled (c) SST-2, slow cooled (d) SST-2, fast cooled

Figure 12: The micrographs of the metal simulants of the two compositions were taken during Vickers Hardness Testing. For each composition, the metal simulant was subjected to both slow cooling and air quenching as a preliminary evaluation of time-temperature transformation behavior.

5.3 Pressure Vessel

The Vickers Hardness Testing revealed important yield strength values to be used to evaluate volume of metal needed for various pressure vessel sizes. The results revealed the most efficient method of processing for constructing the largest vessels for the smallest amount of metal. Figure 13 shows that this method is the one used for sample SST-1, fast cooled: the unenriched regolith which was cast and allowed to cool quickly. Furthermore, the results show that this processing method is the most efficient under the diameter range of 7 m to 12 m. In regards to what was considered to be metal performance needs, preliminary models showed maximum necessary yield strengths of 24,318 MPa and 14,185 MPa. The results of the Hardness Testing did not meet these maximum values. The largest value achieved for yield strength during the tests was the 361.5 MPa for sample SST-1, fast cooled. This allows for a pressure vessel of diameter 7 m and thickness 0.0098 m or a vessel of diameter 12 m and thickness 0.0017 m. Though the testing did not result in values

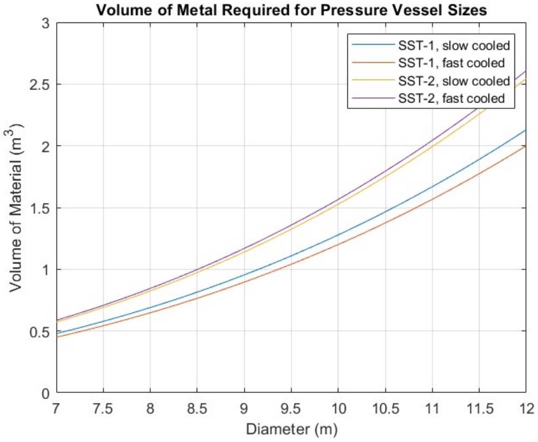


Figure 13: Amount of material needed for the various small scale testing samples to create pressure vessels of varying diameters

that would make pressure vessels of the designed range, they will allow for pressure vessels to be made of different dimensions.

5.4 Conclusion

As seen in the report, the team demonstrated the ability to build an MRE reactor for the moon on Earth, reaching a TRL 4 with the intention of TRL 4/5 by verification testing (coming soon), for the extraction of steel from lunar regolith. The steel was then put through remelting and casting, as relevant manufacturing processes for building metal products, and characterized and tested to analyze the metallurgical and mechanical properties of the produced lunar steel. Through the demonstration of the quality of the steel produced, calculations for the dimensions of a pressure vessel on the moon were done to demonstrate the possibility of producing pressure vessels, such as habitats and fuel tanks, on the moon using lunar steel.

Key innovations for the MRE process and reactor demonstrated by the project for the lunar environment:

1) Steel extraction in vacuum environment - The small scale test demonstrated that the extraction of steel was possible in a vacuum environment such as the floating zone furnace resulting in the separation of lunar steel. (Bumps MRE reaction to TRL 4/5)

2) Steel extraction from unbeneficiated lunar regolith - Steel was successfully produced from unbeneficiated regolith, though inefficiently. (TRL 4/5)

3) Automation of the collection of the extracted metal using the SIS+ER - A successful subsystem demonstration of the slicing off of solidified extracted iron from the iron electrode was performed. (TRL 4)

4) Improving the efficiency of the electrolysis process by removing oxygen bubbles stuck to the electrodes using a sonicator - a proof-of-concept test was performed on carbonated liquid which demonstrated that the sonicator was able to remove the bubbles from the electrode stuck inside the carbonated water as well as the entire liquid. Further calculation reinforced that the sonicator would be able to do the same for the MRE reactor. The sonicator will be tested on the MRE reactor before the competition. (TRL 3)

5) Manufacturing of Steel in Vacuum - the remelting and casting of the steel was done in a vacuum to simulate lunar conditions successfully and resulted in quality steel that can produce pressure vessels on the moon. (TRL 4/5)

While the scope of the project is large, the main designs come from feasible/credible Earth technology that has been modified to fit the specifications for operations in a lunar environment. The design, demonstration, and testing performed in this project show promise for scaling up to be used on the moon for a variety of mission scenarios (such as different regolith, variation in beneficiation, and different pressure levels for the pressure vessels) after the path-to-flight operations have been completed.

5.5 Summary of novel demonstrations

Two novel and highly impactful subsystem concepts, and three unique, low-cost testing approaches for relevant environment testing were demonstrated as part of the ARTEMIS Steelworks project.

5.5.1 Demonstrations of unique subsystem concepts

Exploration of the design space before and after the initial proposal, motivated by a need to simplify processes and improve system longevity and reliability, led to the design, development and demonstration of the following two novel subsystems:

1. A sonicator subsystem was demonstrated, which mitigates the reduced buoyancy force in reduced gravity fields and increases the productivity and efficiency of electrolysis reactions while also extending electrode life. This high-impact innovation has applicability beyond lunar molten regolith electrolysis, with any type of lunar, martian or terrestrial electrolysis process. See section 5.1.3.

2. A novel solid metal puck production process was demonstrated which eliminates the hazard of transferring molten metals between vessels. The iron and slag output of the Molten Regolith Electrolysis reactor is in solid form, accreted at the end of the extraction rod, and harvested using an automated saw unit, the Slag and Iron Slicer + Extraction Rod (SIS+ER)). The solid-state output approach enabled by this fully automated subsystem extends system life, supports process reliability and repeatability, and reduces the need for astronauts to become physically involved in the iron-production pipeline. See section 5.1.4.

5.5.2 Innovations in test setup

Three unique configurations for low-cost testing under relevant lunar conditions were demonstrated.

1. Molten Regolith Electrolysis on unbeneficiated lunar highlands regolith simulant was demonstrated, indicating the physical compatibility of the selected process with the most commonly available input (see section 4.1). The resulting metal was an acceptable steel alloy with 70% Fe, 20% Ti, 10% Si. However, the quantity of metal relative to slag was very small, indicating that a prior beneficiation step could be attractive.

2. Small-scale testing in a vacuum simulating part of the lunar environment was demonstrated (see section 4.3.1). The demonstrated testing approach supports rapid exploration of the input-output space and a productive search for ”designer steel alloys”, where the composition of the steel is a function of the regolith input and the number and type of beneficiation steps to which it was subjected before input into the reactor.

3. Metal manufacturing process was demonstrated in a vacuum, again simulating the lunar environment (see section 4.3.4). The solid pucks sliced by SIS+ER were melted and cast in a vacuum, enabling the characterization of the properties of a steel manufactured from lunar regolith that was both extracted produced in relevant conditions.

6 Technical Management

6.1 Project Management Approach

The team has 2 co-leads. Palak Patel focused on the overall project management and metals manufacturing, characterization, and testing management. Jose Soto focused on the mechanical ARTEMIS Steelworks subsystems management and build strategy, focusing on the integration of the numerous mechanical subsystems to the final MRE reactor design. The lead designer, Zachary Adams, was in charge of the high level design and build of the MRE reactor, also being present to supervise the work in the laboratory the MRE reactor was built in, ensuring safe and efficient operation in lab. The Summer of 2023 focused on the assembly and manufacturing of the final ARTEMIS Steelworks design. Undergraduate students focused more on the building of the different subsystems of the MRE reactor. The leadership team met and communicated weekly to ensure the work was on track, as well as practice agile management: regrouping and reassessing priorities and plan while the project progressed. Subteams met weekly to develop their design and build, supplemented by weekly ”All Hands” meetings intended to keep the rest of the team informed about each subsystem and the ongoing work- ensuring that ever-important interfaces were being properly communicated about. Closer to the deadline of the project, subteams met more often to complete their part of the project to leave adequate time for integrate them while the co-leads dedicated more time ensuring everything was running smoothly.

The project was designed to have contingency plans in case of unplanned obstacles. In the case of unavoidable unplanned events, large lead times, and unavailability of resources, the team made sure to exercise flexibility, regrouping to brainstorm ideas on how to move forward from the inconvenience. The team was very resilient and flexible and knew how to change the design when faced with uncertainties. Due to a constraint on the part of approval of the physical set-up of the MRE reactor as well as broken heating elements, the demonstration of a working MRE reactor was delayed and the results will be included before the competition.

6.2 Detailed Timeline, Including Development and Verification Testing

Feb’23 - March’23 - MRE reactor design, steel manufacturing steps brainstormed

April’23 - MRE reactor design changed and approved by Prof. Allanore, determined what new parts needed to be ordered, steel manufacturing steps determined

May’23 - MRE reaction in vacuum environment as proof of concept, MRE reactor parts ordered, midterm report

June’23 - SIS+ER design, sonicator design considerations, safety training for machining, safety training for melting, casting, sample preparation, characterization, and testing.

July’23 - SIS+ER parts ordered, sonicator ordered, online safety trainings to enter lab space for MRE reactor, training for melting, casting, sample preparation, characterization, and testing.

Aug’23 - SIS+ER built, sonicator testing and calculations to integrate into MRE reactor, lab specific safety training for MRE reactor building,

Sept’23 - MRE reaction in vacuum environment, MRE reaction with non-beneficiated regolith, MRE reactor sub-assemblies and testing, steel melting and casting.

Oct’23 - Final integration of MRE reactor - ready for approval (heating element broke), steel characterization and testing, sonicator proof-of-concept testing, SIS+ER subassembly testing on iron electrode.

6.3 Safety

All experiments were performed in accordance with the MIT Department of Material Science and Engineering’s Chemical Hygiene Plan, with primary risks identified as being the use of large electrical currents, exposure to fumes, and inhalation of small particles from the lunar regolith simulant. Recommendations specific to the operation of the molten oxide electrolysis cell are described below.

Machining of parts for the MRE reactor will be performed in machine shops under the supervision of machine shop supervisors wearing the correct PPE (safety glasses). During loading, loose or sintered regolith is added to the reactor vessel. Safety glasses, nitrile gloves, lab coats, shoes without a tendency to trap dust, and respirators will be worn. The power supply should be disconnected to guard against the potential for electric shock, and the regolith pre-heated to reduce the possibility of a molten metal explosion from water contamination. PPE will continue to be worn during reactor operation, including safety glasses, lab coats, and gloves. Operators will be standing far from the reactor during the majority of the time. Operators will also monitor reactor parameters (pressure, temperature, operating voltage) as it is heated via a low voltage (1-5V), high amperage (500A) alternating current. If reactor conditions become uncontrollable, such as from runaway pressure or temperature, power to the cell should be cut off immediately. If automatic cooldown procedures fail to mitigate the situation, operators should leave the lab to let the reactor cool down. If the reactor still cannot be brought under control, the fire alarm should be activated to evacuate the building. In the event that the reactor's carbon monoxide or carbon dioxide monitors trigger, emergency shutdown will occur and the operators will leave the lab. If gas leaks out of the lab or does not dissipate, the lab-wide alarm will be triggered and the fire alarm should be pulled, resulting in a building evacuation. Metal produced after the reaction will be polished wearing correct PPE, using fluids to prevent inhalation of the metal and tested under safe conditions set by the laboratory.

The above steps will be performed by graduate students or trained professionals; undergraduates may not perform any potentially hazardous procedures without prior written approval from a supervisor.

6.4 Compliance with Requirements and Constraints

Table 5: Proposal compliance with constraints and guidelines of BIG Idea Challenge.

Criterion	Compliance notes	Sec. #
Innovative	Sonicator for O_2, automation, unbeneficiated regolith usage	5.5
Realistic	MRE demonstrated to TRL 4	2.1
Cost-effective	Fewest, easiest inputs; low complexity; MOE is being commercialized on Earth	2.1
Flexibility	Reaction feasible even before beneficiation implemented	4.3.1
Stakeholders	NASA invested in MRE; Moon-to-Mars feed-forward; lunar economy needs space	2
Tech qualify	Sonicator will be TRL 4 by Nov 2023	4.3.3
Ease of use	Designed for teleoperation; Bottom half of system easily replaceable for maint.	3.1
KPI Verify	Battery of compositional, microstructural and mechanical tests on steel output	4
Lunar Analog	Regolith simulant; small scale reactions in vacuum, large scale in inert gas	3.1, 4.3.1
Efficiency	95% of oxygen extracted; has low embodied energy at system-of-systems level	2.1
CLPS Lander	Mass budget CLPS-compatible; energy compatible with ongoing LVSAT or FSP	3.1
Fabrication?	Descriptions of materials and fabrication process provided	3.1, 5
Sustainability	Larger reactors are more reliable, reusability, automation	3.1
Scalability	Able to upscale for large scale developments.	3.5

6.5 Budget

ARTEMIS Steelworks Budget vs Actuals to Date 10/23/2023

	From Phase 1 funds	From Phase 2 funds	TOTAL	
Materials and Services	$ 24,439.47	$ 6,109.87	$ 30,549.34	
B2P Purchase Orders	$ 13,215.90		$ 13,215.90	
Subtotal Materials				**$ 43,765.24**
Full time Research Stipends x 8	$ 9,300.00	$ 43,500.00	$ 52,800.00	
Subtotal Labor				**$ 52,800.00**
Overhead	$ 2,657.83	$ 1,321.58	$ 3,979.41	
Subtotal Overhead				**$ 3,979.41**
Credit for future testing at NASA		$ 10,000.00	$ 10,000.00	
Flights x 15	$ 3,484.20		$ 3,484.20	
Meals x 15	$ 300.00		$ 300.00	
Hotel	$ 2,388.00		$ 2,388.00	
Registration	$ 8,250.00		$ 8,250.00	
ASCEND travel costs x 4	$ 6,747.00		$ 6,747.00	
IEEE travel costs x 4		$ 9,800.00	$ 9,800.00	
Subtotal Travel				**$ 40,969.20**
Total Spent or Commited 10/23/2023	**$ 70,782.40**	**$ 70,731.45**		**$ 141,513.85**
Total originally budgeted	**$ 81,372.26**	**$ 95,221.50**		**$ 176,593.76**
% spent or committed	**87%**	**74%**		**80%**

Funds from Other Sources: MIT UROP Office, MIT UA, and MASGC	MIT UROP	MIT UA	MASGC	
Palak Patel			$ 500.00	
Derek Chan		$ 1,000.00	$ 500.00	
Amber Cooper		$ 700.00	$ 500.00	
Jose Soto		$ 1,000.00	$ 500.00	
Alice Zehner		$ 500.00	$ 500.00	
Christopher Kwon			$ 500.00	
Helena Usey		$ 500.00	$ 500.00	
Jonatan Fontanez		$ 500.00	$ 500.00	
Thomas Nguyen			$ 500.00	
SWE Fund for our 4 undergraduate women	$ 400.00			
Department of Aero/Astro Support for Amb	$ 415.00			
Totals	$ 815.00	$ 4,200.00	$ 4,500.00	
Total received from other sources				**$ 9,515.00**

Total Spent or Committed on Project as of 10/23/2023	**$ 141,513.85**
Of which, funded by MIT and MASGC travel grants	$ (9,515.00)
Net amount spent from original grants	**$ 131,998.85**
Remaining funds from original grants to be spent on continued testing to TRL 5	$ 44,594.91
Total of original grants	**$ 176,593.76**

7 Path-To-Flight

The main path-to-flight modifications for a 2028 technology demonstration mission are described below.
Integration with a lunar regolith delivery and enrichment system: For the lunar demo mission, we assume that lunar regolith on the Moon is collected by a third party, such as the RASSOR rover, and enriched to a target of 40% Fe grade by mass by a beneficiation step. This critical input step will be validated by testing on Earth, and it is assumed that, in the technology demonstration flight, Honeybee's magnetic separation approach will be tested in series with the molten regolith electrolysis.
Modifications to the input/output management: The regolith hopper will be modified such that the enriched lunar regolith can be automatically delivered by the delivery and enrichment system and fed to the reaction chamber through the top of the hopper now exposed to the environment. The alloying hopper will be replaced with an alloying dispenser system which will contain a limited amount of alloying elements brought inside of it from Earth to demonstrate the alloying process.
Autonomous remelting and casting system: A fully autonomous melting and casting system capable of pouring of the liquid metal produced on the Moon into the cast(s) brought from Earth shall be developed for the demo mission.
Data, telemetry and control: Additional telemetry and telecontrol capabilities will be required for a lunar technology demo mission to ensure control of the MRE cell from Earth and transmission of the experiment data to Earth. Those capabilities should be integrated with and supported by the respective lander capabilities. Additional data acquisition capabilities to measure characteristics of the cast samples shall also be designed. A cargo return option can be considered for the cast samples.
Power: Due to high power requirements, the lander power capabilities will likely be insufficient for the cell operation on the Moon. A separate power source (such as a 10kW NASA fission reactor, or a vertical solar array) might need to be delivered to the Moon together with or before the demo mission. An alternative option is reducing the power needed for the process by increasing the time of extraction.
Additionally, the following measures shall be implemented for the entire system: (1) design and testing for launch (vibration, acoustics, constraints); (2) radiation hardening of avionics and power controllers; (3) extensive testing of automation and autonomy systems; (4) packaging and integration for lunar surface operations and lander integration; (5) extensive thermal modeling and trade studies for location of device to take advantage of lunar thermal environment; (6) dust mitigation and tolerance solutions for all mechanisms.

All components that comprise the SIS+ER and MRE require lunar-dust mitigation, thermal management, and radiation protection qualifications prior to the deployment of this system in the lunar environment. For each of these subsystems, in addition to the necessary radiation hardening, thermal protection, and weight-saving redesigns, the revisions required to meet these qualifications and successfully operate in the lunar environment generally fall into two categories: overall system redesigns and component introductions.
The Molten Regolith Reactor does not require crucial redesigns for its operation in a finalized architecture. Arguably, since the reactor consists of a furnace with the majority of space reserved for insulation, a flight-ready equivalent would involve swapping the thermal insulation with a radiator to regulate the reaction temperature. Similarly, the current fluid-based cooling system for the caps would be rendered impractical in the lunar environment, further warranting the use of an alternative heat-managment system.
Furthermore, the team could not safely implement an autonomous capability to the furnace: all operations required a human operator due to the sensitivity and cost of the Carbolite Furnace employed. A future prototype would require the incorporation of a digital system capable of initiating, monitoring, and controlling the reaction autonomously - regulated only by a series of uplinked commands from the Earth.
Finally, the Molten Regolith Reactor requires some structure for the introduction of beneficiated lunar feedstock. Originally, the team intended to do so with a hopper, but depending on the design of the beneficiation method employed in tandem with this reactor, there may very well exist a different physical or electrome-

chanical interface. This element of the path-to-flight plan is a necessary addendum but does not pose a significant problem for the flight readiness of this system.
On the other hand, the SIS requires significant improvements both in design and capacity to fully meet all its objectives. First, the implementation of dynamometers to measure cutting forces would be sufficient to program a feedback loop to control the rate of cutting during the slicing process. Secondly, the current design incorporates an off-the-shelf saw. A flight-ready system would require a saw outfitted with a radiator to dissipate heat generated by the blade as well as an autonomous blade-replacement process to limit the need for astronauts to interact with the architecture.
Thirdly, linear actuation rods can be outfitted with bellows to protect both against external lunar dust and iron shavings accumulated during the sawing process. Fourthly, once the system cuts iron, to ensure that the cathode can fit within the furnace, a deburring unit must be incorporated into the current design. In the interest of time, the team did not manufacture a solution to the deburring problem, but it did propose the use of a rotational deburring blade that could also be automated and incorporated into the iron-cutting subsystem. The combination of all of these redesigns would both prepare the system for use in the lunar environment but also guarantee that the slicing process would occur without any astronaut intervention other than the collection of generated iron and discarded blades.
Before building flight hardware, it is worthwhile to investigate the efficacy of the furnace on its side. Doing so would both lower the system's center of mass for greater stability and allow more space for a longer Extraction Rod. Furthermore, it would reduce the complexity of the Back Rod Opposer, since one could use a fixed structure as support for the cutting process, akin to the process of manually sawing stock with a table providing stabilization. In fine, each of the design reviews listed above would bring the iron-producing architecture listed above closer to its intended vision as a fully independent agent in the lunar steel-producing pipeline.

Future work can be done to further develop the MRE process including testing to optimize the voltage settings to extract a more optimized lunar steel alloy. Work can also be done to determine which beneficiation process is best for the enrichment required for the MRE process. More tests can be run on the MRE reactor to determine the work-life of the reactor.

8 Bibliography

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Appendices

The Appendices contain additional detail of analyses carried out during our design process. They are intended as optional, supplemental reading; the key findings from the detailed analyses shown here are summarized in the body of the proposal.

A Stakeholder Value Network

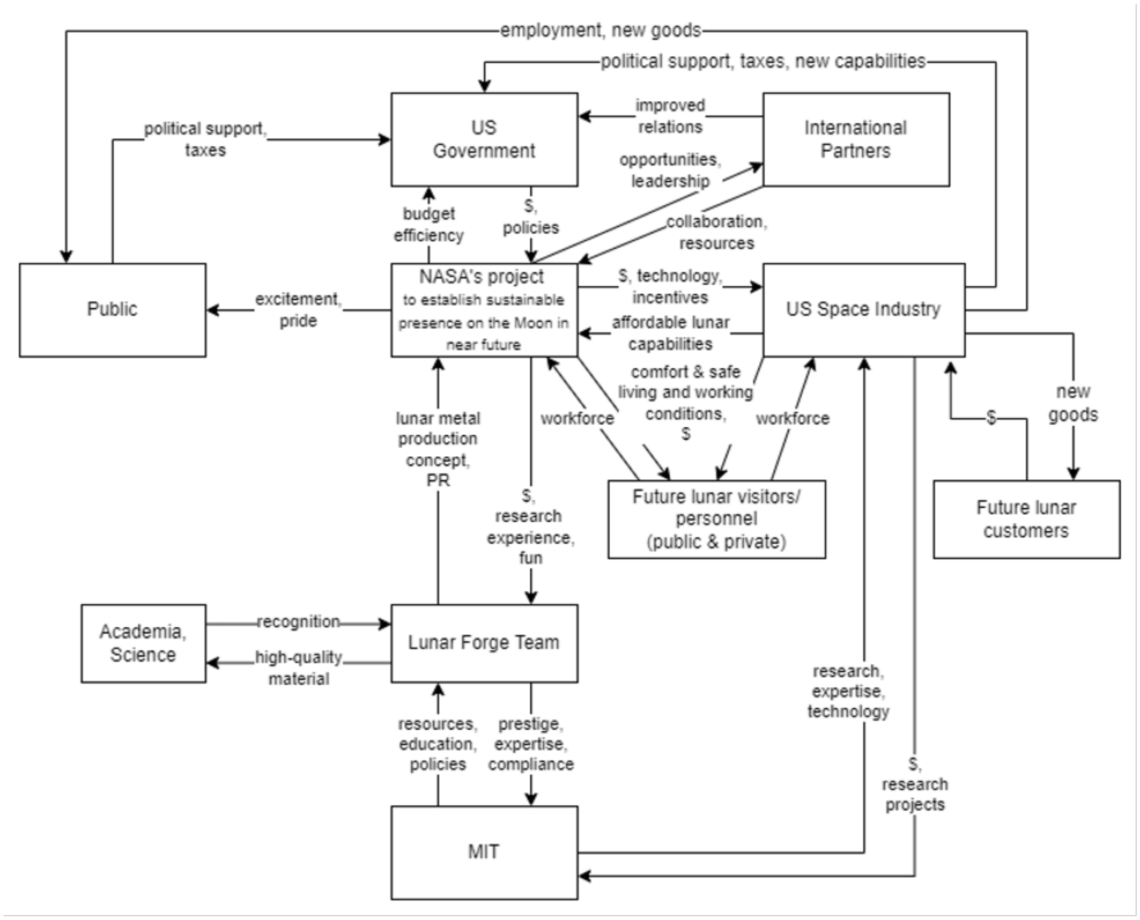

Figure 14: Lunar steel stakeholder analysis